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ABSTRACT

High-temperature strength, resistance to corrosive atmospheres, and moderate cost combine to make ceramic materials an obvious choice for construction of high-temperature thermal energy recuperator systems. Despite these advantages, ceramic recuperators are steadily being replaced by metallic units at considerable sacrifice in maximum air or fuel preheat temperatures and hence in recovery efficiency. This is because existing ceramic designs contain a large number of cemented joints which, under the influence of differential thermal expansion and vibration, tend to open up and produce very large leakage rates between the exhaust and preheat streams. By constructing a recuperator from ceramic heat pipes, the number of joints and the thermal stress to which they are subjected can be greatly reduced, and very low leakage rates can, in principle, be obtained. Methods of fabricating ceramic heat pipes are described and a conceptual recuperator design is presented. Potential applications of this type of unit are also briefly discussed.

INTRODUCTION

The major loss of energy in high-temperature furnaces used for steelmaking foundries, glass manufacturing and a wide variety of other applications results from high-temperature gases exiting up the flue. Because of the widespread use of these furnaces in industrial processing, flue gas loss constitutes a significant fraction of the total energy wasted in the United States each year. In many operations, recuperators or regenerators are used to recover some of this energy. Because they operate continuously, recuperators are generally favored over regenerators despite their lower temperature capability.

Ceramic recuperators, once widely used in industry, have fallen into disfavor and have largely been replaced with metallic units using a variety of iron-, nickel-, and chromium-based alloys. In Europe the replacement is virtually complete. The main reason for this shift is that conventional ceramic recuperator construction requires a large quantity of sometimes intricate ceramic blocks to be cemented together in a checkerwork array providing separate passages for air and waste gas streams. Not only are these units massive, and hence expensive, but they quickly tend to develop very high leakage rates from the higher pressure air side to the waste gas passages because vibration and thermal cycling cause the many joints to open up. The metallic units tend to be cheaper and much less leakage prone. However, their preheat capability for incoming air is very modest, usually limited to 650 C. Considering that the temperature of the exhaust gas is frequently in excess of 1500 C, this suggests that energy recovery efficiency is on the order of 40% or less. Radiation recuperators are highly touted for their ability to accept flue gases at temperatures of up to 1500 C. Nevertheless, their preheat capability is only on the order of 600 C and they suffer the additional disadvantage of high pumping power requirement because they need high velocity incoming air flow in order to function properly.

In order to construct efficient, high-temperature recuperators, it appears likely that a return to ceramic designs is required. Work is currently in progress at British Steel Corporation (BSC)[1,2] on a ceramic recuperator that minimizes the number of joints by using flexible seals to produce a tube-shell-type heat exchanger. The general configuration is shown in Fig. 1. A prototype model of this exchanger has performed very well, with a leakage rate restricted to 3%. Air preheat temperature was a modest 650 C, but uprating to 780 C appeared feasible.

The requirement in the BSC recuperator for a crossflow-counterflow combination to achieve high effectiveness means that headers are required to reverse the air flow. They contribute to the complexity and cost of the design and increase the pumping power requirements relative to a straight counterflow design. These difficulties, as well as the requirement for flexible seals and lack of redundancy, can be avoided in the design of a counterflow heat pipe recuperator. Additionally, the number of potential leakage paths can be reduced by a factor of two.

In order to build a heat pipe high-temperature heat exchanger, the first requirement is a high-temperature heat pipe capable of withstanding the high-temperature waste gas environment and having no more than moderate cost. Heat pipes fabricated from refractory metal alloys, protected with ceramic or other types of coatings, are one possible approach. However, the cost is likely to be prohibitive. Another possible approach--the one described here--is the ceramic heat pipe.

CERAMIC HEAT PIPE DESIGN

Ceramics with excellent high-temperature properties, e.g., SiC, SiN, and various oxides are available in tubular form, with some of these, particularly SiC, Al_2O_3, and Mullite, being readily obtained with sufficient density to be impervious to gas penetration. Others such as SiN are available, in large sizes, only with interconnected porosity. However, glazing compounds have been developed that can effectively seal these materials. Constructing heat pipes directly from ceramic materials is infeasible primarily because of chemical incompatibility with high-temperature heat pipe working fluids. (The two best candidates for the latter are sodium and lithium in the temperature range required for high-temperature recuperators.) A way to circumvent this potential problem and still stay within the bounds of moderate cost--the main thrust of this discussion--is to use chemical vapor deposition (CVD) techniques to line the inside wall of ceramic tubes with thin, impervious layers of refractory metals or refractory metal alloys. Metals such as tungsten, molybdenum, and niobium have shown excellent resistance to attack by sodium and lithium and considerable experience in depositing thin, impervious layers has been obtained with 0.1-mm-thick tungsten layers on the inside of Nb-1Zr tubes. The latter work was done in the development of Nb-1Zr/UC fuel rods for space power (nuclear reactor) supplies because of the need to protect the niobium alloy from chemical reaction with the carbide fuel. Well-bonded tungsten layers have also been applied to SiC by the CVD method.

A sketch of the proposed ceramic heat pipe design is shown in Fig. 2. It has the following design features:

1) Chemical vapor deposition of a thin impervious metal layer to protect ceramic from working fluid and provide a surface known to be wet by sodium or lithium. The ceramic must provide, in addition to structural strength, protection for the metal liner from the high-temperature waste gas environment. Therefore, it should be relatively (though not necessarily perfectly) impervious to gas permeation. Because the required metal liner thickness is on the order of

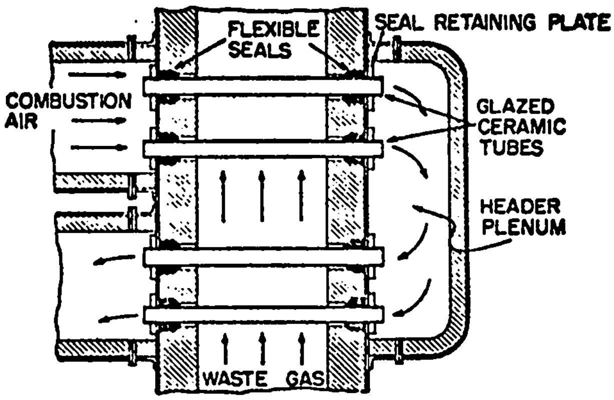

Fig. 1.
Corporate Engineering Laboratory ceramic recuperator.

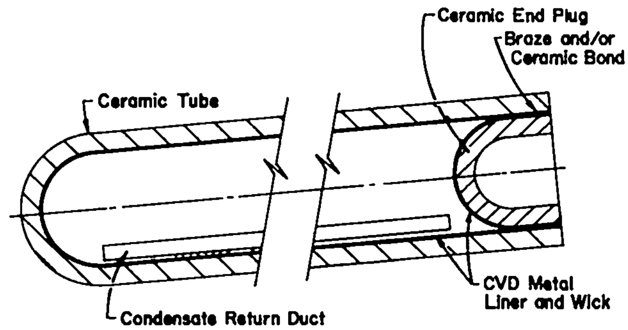

Fig. 2.
Ceramic heat pipe.

only 0.1 mm (4 mils), its cost will be about 10% or less of the cost of the ceramic tubing. (Inquiries on CVD prices have indicated that the total cost per unit weight of deposited metal liner will, in large-scale production, be about twice the prevailing cost of the metal in powder form.)

2) Rounded ceramic closure of one end of tube. This eliminates the necessity of providing a high-temperature seal in the combustion product section of a unit. If necessary, a double-ended seal configuration can also be used, either by designing the recuperator so that the braze seals are in a more quiescent and lower temperature environment or by designing the closure joint so that a reaction bond of the ceramic protects the braze seal.

3) Re-entrant braze seal design. This permits a temperature drop to be taken between the operating portion of the heat pipe and the braze seal, and hence reduces the difficulty in providing a durable and reliable seal joint. Because the length of the braze joint can be extensive, limited corrosion can be tolerated. Tungsten or other metallizing of the mating surfaces, with or without CVD overcoating, and with any of a wide selection of high-temperature brazes, provides one method of fabricating this seal. Reaction bonding of the end plug to the tube wall can be used, particularly with SiC, to form a double seal with high corrosion resistance.

4) Bonding of liner. Some degree of mechanical bonding is available from the CVD method of application. In practice the thermal expansion of the liner should be slightly greater than the ceramic tube to assure good contact at temperature. This situation exists for tungsten and SiC. For niobium and Al_2O_3, the expansion coefficients are nearly identical. Co-deposition of

molybdenum and tungsten (or other refractory metal combinations) can be used to adjust the coefficient of thermal expansion of the liner to that of the ceramic over a limited range. An additional force to maintain good thermal contact of the liner to the ceramic tube is provided by the vapor pressure of the working fluid. (Bonding to Al_2O_3, Y_2O_3, and, presumably other ceramics is possible by first tungsten-metallizing the surface and then applying the CVD liner. This is obviously more expensive and very likely unnecessary.)

5) Wick design options. The wick capillarity required for gravity-return heat pipe design is only that needed to give circumferential distribution of the working fluid. Hence, the following are a few of the wick design options:
   a) Powder slurry dip with subsequent sintering to provide a porous film of refractory metal.
   b) Photoetching a diamond structure in the liner wall. (This can be done with current processes for molybdenum.)
   c) Metal screen, plug-formed against the inner wall of the ceramic tube--a standard technique with screen cut on the bias (but more costly than other methods).
   d) Chemical vapor deposition application of a diamond structure. Tungsten and molybdenum deposition can be readily controlled to yield columnar crystals over a relatively broad dimensional range. The exposed ends of these crystals have a pyramidal configuration that can serve as the capillary pumping medium for circumferential distribution of the heat pipe working fluid.

6) Flow separator. This provides a channel for gravity-powered fluid return. A wide variety of potential designs is available, if unproven, including one devised for a heat pipe methanator concept.[3] Proven designs include the soon-to-be-patented Q-dot Corporation configuration,[4] although this has the disadvantage of requiring higher working fluid inventory. When vertical orientation of the heat pipes is feasible, open spiral flow channels can be installed in the heat pipe to permit gravity return of a low inventory of working fluid while shielding the return flow from vapor entrainment effects.[5]

RECUPERATOR DESIGN WITH CERAMIC HEAT PIPES

The ceramic recuperator design is not materially different from that used in commercial heat pipe energy recovery units for lower temperature operation (see Fig. 3). The unit is tilted at a slight angle to provide for gravity return of

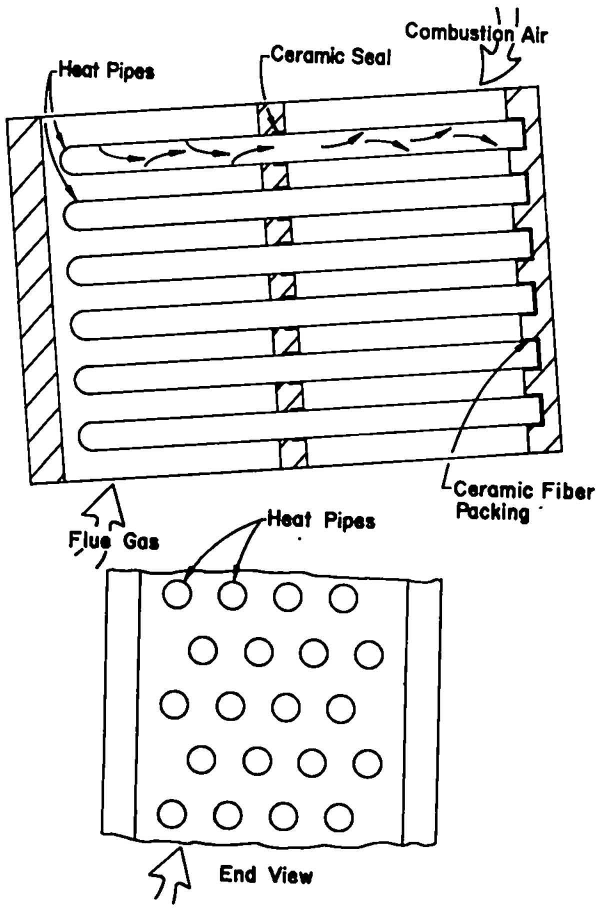

Fig. 3.
Ceramic heat pipe recuperator.

the working fluid. The heat pipes can also be mounted vertically with the waste gas stream flowing through the lower section.

A few of the design advantages over current designs include

1) Counter flow exchange in a simple configuration requiring no flow-reversal headers.
2) One seal per pipe--between combustion air and waste gas sections--which leads to a reduction of potential leakage sites.
3) Minimization of thermal expansion problems because both ends of the tube can move freely.
4) Fixed seals are possible with attendant reduction of leakage rates.
5) High heat transfer capability. This is not limited by radial wall drops, which are small, or by axial temperature drop in the heat pipe which will be insignificant, but rather by the convective and radiative heat transfer coefficient to and from the gas streams. Fluting or finning the ceramic tubes can be used to increase these coefficients. Because the thermal conductivity of ceramics generally is low (SiC excepted), these fins will be short and fat, but any increase in effective heat transfer area they provide will diminish the total number of pipes required for a given capability.
6) Redundancy of operation. Fracture of a tube on one side of the divider will not cause leakage to the other side. For leakage to occur, it would be necessary for the tube to fracture on each side. The same is not true for the recuperator shown in Fig. 1.

7) Potential for guaranteed nonmixing of process streams. Where this feature is essential, it can be done by making the divider a double wall unit. The heat pipes pass through the space between the two walls, but any joint leakage flow enters this space and is pumped away. Hence, cross-contamination of process streams cannot occur. Accomplishing this objective without sacrificing heat transfer efficiency appears to be unique to heat pipe systems. In the present case it would require flexible seals in one half of the double partition.

8) Ease of cleaning--the whole divider/heat pipe unit can be lifted out to accomplish this.

9) Potential for relatively easy replacement of individual heat pipes.

10) Potential very high combustion air preheat temperatures.

It is anticipated that a unit of this type would be used in series with a more conventional unit that accepts waste gas at less than 1000 C and provides the initial heating of the combustion air.

OTHER APPLICATIONS

1) With some design modification, the ceramic heat pipe recuperator could be used with a fluidized coal bed (or other coal-fired furnace design) to transfer heat from the combustion zone to a high-temperature air or inert gas heater region, with the gas being used to drive a turbine in a combined cycle (gas turbine/Rankine) generator system. (Coal cannot be used directly because of particulate content that tears up the turbine blades.)

2) In indirect coal gasifiers, where heat must be transferred from a combustion chamber to a steam-coal reaction chamber at 1100 C, the ceramic heat pipe could provide the structural integrity and resistance to corrosion and erosion necessary for the successful operation of such a gasifier.

3) In coal-fired MHD units, the ceramic heat pipe heat exchanger could be used as an air preheater for open-cycle conversion or as a gas heater for closed-cycle systems.

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